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SURFACE X-RAY EMISSION FROM NEUTRON STARS

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Galactic x-ray emission has been observed from rockets[1] and recently[2] two discrete sources of x rays in the wavelength region of 1.5 to 8 Å have been found. The measured flux over this wavelength region was 10^{-7} erg/cm² sec for the stronger source (located near Scorpius) with an angular size less than 5°. The other source is about eight times weaker and seems to coincide with the Crab Nebula. The Crab is known to be the remnant of the supernova in A.D. 1054, three thousand light years away. The stronger Scorpius source may[3] be a (somewhat closer) supernova remnant of similar age.

During a type I supernova explosion, the core of the original star may contract into a hot "neutron star." Such neutron stars were suggested[4] as possible x-ray sources and we give analytic estimates[5] of their observable surface properties as a function of age (for central temperatures of the order of 10^9 °K).

Neutron stars can exist with masses between about $0.2M_\odot$ and $1.5M_\odot$ ($M_\odot \approx 2\times10^{33}$ g is the solar mass) and have a radius R close to 10 km and interior densities a few times 10^{14} g/cm³. The neutrons are highly degenerate for central temperatures $T_c \ll 5\times10^{11}$ °K and their average Fermi energy $E_{F,n}$ is about 50 MeV. Because of the high conductivity, the neutron core is essentially isothermal and its total thermal energy E_t is[6] approximately

$$E_t = 7.6\times10^{47}(T_c/10^9 \text{ °K})^2(M/M_\odot)$$

$$\times (E_{F,n}/50 \text{ MeV})^{-1} \text{ ergs.} \qquad (1)$$

The neutrons are in equilibrium with a small amount of protons and electrons with $E_{F,n} \approx E_{F,e}$ ($E_{F,p}$ is small). Neutrinos can be emitted by a modified "Urca process" in which two neutrons with suitable momenta (near the Fermi momentum) "scatter" into a final state of $n+p+e^-+\bar\nu$ (the inverse process releases ν).¹ Our present[7] estimate for this Urca energy loss rate, $L_{\nu,\text{Ur}}$ is

$$L_{\nu,\text{Ur}} \sim 2\times10^{36}(T_c/10^9 \text{ °K})^8(E_{F,n}/50 \text{ MeV})^{-2.25}$$

$$\times (M/M_\odot) \text{ erg/sec.} \qquad (2)$$

At densities below 10^{11} g/cm³, the equilibrium configuration favors "ordinary ionized matter" which constitutes a thin mantle (~1 km) around the neutron core. Throughout most of the mantle the electrons are relativistically degenerate with a high conductivity, so that the temperature is close to T_c, and one can calculate the "density scale-height" analytically. The plasma neutrino process[8] has a maximum rate at densities near $(T/10^9 \text{ °K})^3\times4\times10^{10}$ g/cm³ and we find for the integrated energy loss rate $L_{\nu,\text{pl}}$

$$L_{\nu,\text{pl}} \approx 2\times10^{26}(T_c/10^9 \text{ °K})^{10}(R/10 \text{ km})^4$$

$$\times (M/M_\odot)^{-1} \text{ erg/sec.} \qquad (3)$$

When $\rho < \rho_{1\lambda} \approx (T/10^9 \text{ °K})^{1.5}\times10^6$ g/cm³, the electrons become nondegenerate and their conductivity low. The main temperature gradient then occurs in an outer nondegenerate layer (a few meters thick) of "ordinary matter." We assume $T = T_c$

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at $\rho = \rho m$, a constant opacity κ ($\kappa^{-1}\rho^{-1}$ is the photon mean free path), and $A/Z = 2$ in this layer, and obtain its structure analytically. The photon luminosity L_{ph} is then

$$L_{ph} = 1.6 \times 10^{37}(0.2/\kappa)(M/M_\odot)$$

$$\times (T_c/10^9 \,^\circ K)^{1.5} \text{ erg/sec,} \quad (4)$$

independent of the radius R. For $T_c \gtrsim 5 \times 10^8 \,^\circ K$, Thomson scattering of photons by free electrons dominates which gives $\kappa = 0.2$. For $T_c \lesssim 2 \times 10^8 \,^\circ K$ the opacity κ depends on temperature (roughly as $\rho^{0.5}T^{-3.5}$), due to photon absorption by a small admixture of bound electrons. We estimate an average value of 0.4 for κ at $T_c = 2 \times 10^8 \,^\circ K$.

Table I gives our results for several values of the central temperature for mass $M = 0.5M_\odot$ and radius $R = 10$ km. T_e is the effective blackbody surface temperature corresponding to L_{ph} and the surface area $4\pi R^2$; λ_W is $hc/4.965kT$, the wavelength of the Wien displacement law but with a gravitational red shift of 8% included; τ is $E_t(L_\nu + L_{ph})^{-1}$, a measure of the cooling time. A neutron star with $T_c \approx 10^9 \,^\circ K$ in the Crab Nebula (age $\sim 10^3$ years) would produce near the earth, according to Table I, an x-ray intensity close to that observed.[2] This agreement is gratifying but in view of the large numerical uncertainties[9] in Table I may still be fortuitous.
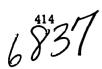
Spectral measurements of discrete x-ray sources in the future will be very useful: At short wavelengths ($\lambda \lesssim 1$ Å) the rapid fall-off of the neutron star's blackbody spectrum should be easy to distinguish from the flatter spectra expected from other[10] types of x-ray sources. If finer spectral resolution is available, intensity discontinuities may be detectable at wavelengths λ_K corresponding to K-shell absorption edges of medium-size nuclei (e.g., 6.3 Å for Mg and 1.3 Å for Fe, before applying the red-shift correction). Measurement of λ_K (or of absorption

lines) would furnish a value for the gravitational red-shift and hence for M/R for the neutron star. For x-ray wavelengths $\lambda \lesssim 5$ Å, absorption by interstellar gas is small even across the whole galactic disc. If x-ray detection sensitivity can be improved by a factor of about 100 over that in previous flights,[1,2] then any supernova explosion which produced a neutron star during the last one or two thousand years could be detected. There could have been up to about 20 such events. Much older neutron stars with $T_e \lesssim 10^6 \,^\circ K$ would be difficult to detect as x-ray sources because of strong absorption at $\lambda \lesssim 30$ Å by interstellar gas. Because of its small radius the energy radiated directly in visible light by a neutron star ($L_{vis} \lesssim 4 \times 10^{27}$ erg/sec $= 10^{-6}L_\odot$) is far too small to be detected in most cases. If the star is situated in a gas cloud (density $\gtrsim 20$ atoms per cm^3) it will ionize a surrounding region (of radius ~ 0.2 light years for $T_e = 10^6 \,^\circ K$; ~ 0.6 light years for $T_e = 10^7 \,^\circ K$). Recombination of the ions results in visible light and the region's surface brightness may be (just barely) detectable by terrestrial optical telescopes.

The chemical composition of the atmosphere of a neutron star is uncertain at the moment, partly because the density scale-heights are so small and diffusion[11] can be much more important than in ordinary stars; H and He from the surface can diffuse in a few years to deeper layers ($T \gtrsim 5 \times 10^8 \,^\circ K$) where they are burned up rapidly and these two elements should be completely absent in neutron stars. The equivalent diffusion time for ^{12}C is about 100 years and C is probably strongly (but not completely) depleted in a neutron star about 1000 years old, O and Ne depleted slightly, and any Mg or heavier nuclei (present at the formation of the neutron star) are unburnt. Diffusive separation can lead in a few hundred years to a strongly enhanced abundance in the photosphere of the lightest nuclei (O, Ne, or Mg), unless convection restores mixing, in

Table I. Emission characteristics.

Core temp. T_c (°K)	Total thermal energy E_t (ergs)	Neutrino loss rate $L_{\nu'}pl + L_{\nu'}Ur$ (ergs/sec)	Photon luminosity L_{ph} (ergs/sec)	Surface temp. T_e (°K)	Cooling time τ (years)	Optimum wavelength λ_W (Å)
2×10^9	1.6×10^{48}	4×10^{39}	2.3×10^{37}	1.3×10^7	10	2.4
1×10^9	4×10^{47}	5×10^{36}	8×10^{36}	1.0×10^7	1×10^3	3.1
5×10^8	1×10^{47}	8×10^{33}	3×10^{36}	8×10^6	1×10^3	3.9
2×10^8	1.6×10^{46}	1×10^{29}	3×10^{35}	4.5×10^6	1.5×10^3	6.8

which case the metals near ^{56}Fe could be most abundant.

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[1]H. Gursky, R. Giacconi, F. R. Paolini, and B. Rossi, Phys. Rev. Letters 11, 30 (1963).

[2]S. Bowyer, E. T. Byron, T. A. Chubb, and H. Friedman (to be published).

[3]Two Arab astronomers, Haly and Albumazar, observed a very bright star, located near this x-ray source, for four months around A.D. 827. They report a brightness "comparable with the quarter moon," which is brighter (and therefore probably closer) than the original Crab explosion. However, no Chinese or Japanese records have been found yet to corroborate this event.

[4]H. Y. Chiu, Ann. Phys. 26, 364 (1964).

[5]Such estimates were first made by R. Stabler (Ph.D. thesis, Cornell University, 1960, unpublished), but he used too large a value for the effective opacity.

[6]S. Chandrasekhar, An Introduction to Stellar Structure (Dover Publications, New York, 1951), Chap. 10.

[7]This estimate is essentially the result of a dimensional analysis and could be in error by several orders of magnitude.

[8]B. Adams, M. Ruderman, and C.-H. Woo, Phys. Rev. 129, 1383 (1963). Other neutrino processes give a rate a few orders of magnitude below those discussed in this paper.

[9]For fixed T_c, our L_{ph} could be in error by factors of 4 or 5 and T_e by factors of about 1.5. L_ν (and hence the cooling time τ) is uncertain by larger factors. D. Morton (unpublished) has made independent estimates of T_e (but not of τ) which agree well with ours.

[10]G. W. Clark, M. Oda, and P. Morrison (unpublished).

[11]E. Schatzman, White Dwarfs (North-Holland Publishing Company, Amsterdam, 1957).